Unit 4
Cell Division

Chapter 10: Meiosis and Sexual Life Cycles

Overview: Variations on a Theme

- Living organisms are distinguished by their ability to reproduce their own kind
- **Heredity** is the transmission of traits from one generation to the next
- **Variation** is demonstrated by the differences in appearance that offspring show from parents and siblings
- **Genetics** is the scientific study of heredity and variation

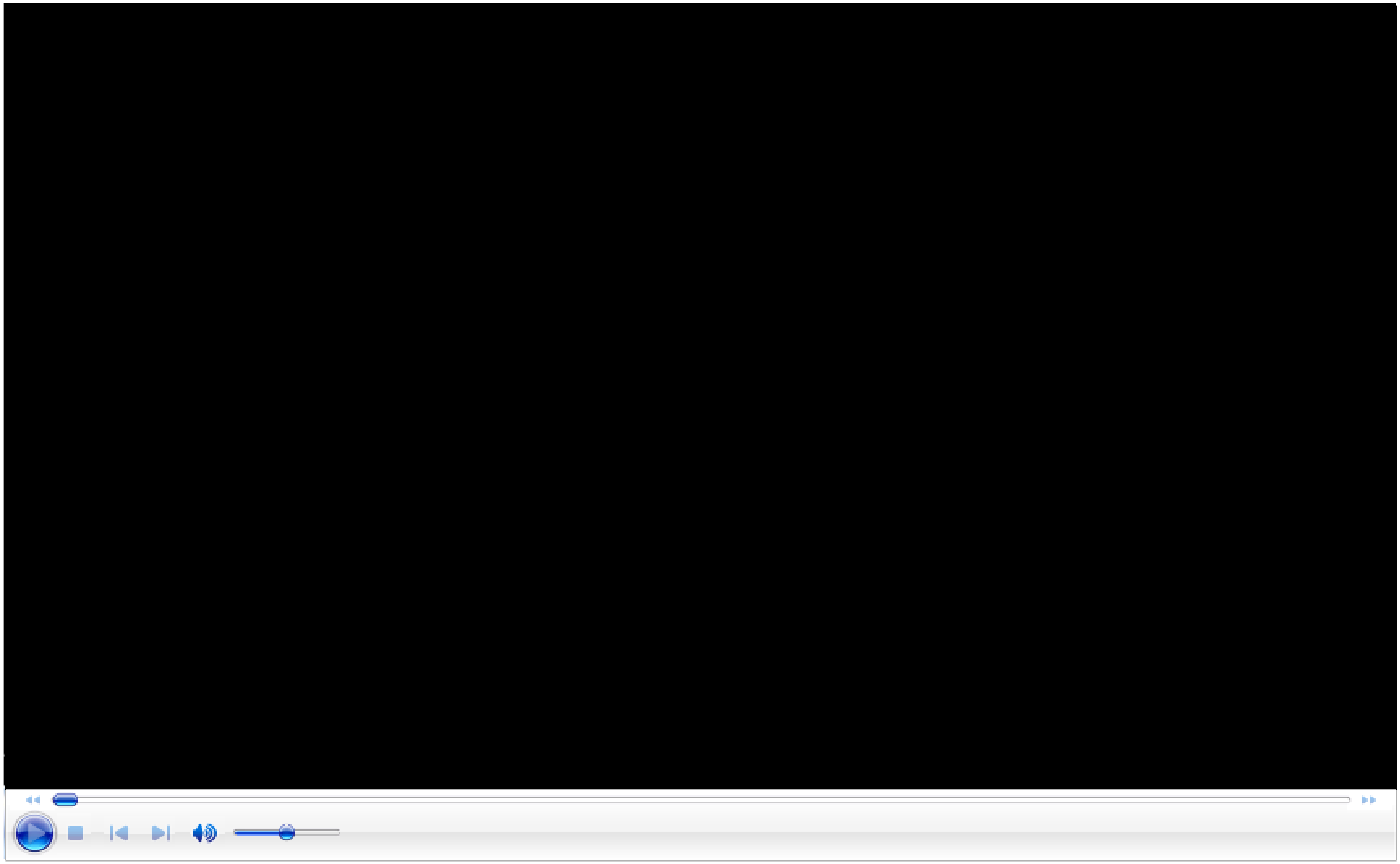
Concept 10.1: Offspring acquire genes from parents by inheriting chromosomes

- **Genes** are the units of heredity and are made up of segments of DNA
  - Inherited information is passed on in the form of each gene's specific sequence of DNA nucleotides
- Genes are passed to the next generation via reproductive cells called **gametes**
  - Sperm and eggs

- Most DNA is packaged into chromosomes
  - Humans have 46 chromosomes in their **somatic cells**
    - The cells of the body except for gametes and their precursors
- Each gene has a specific location, or **locus**, on a certain chromosome

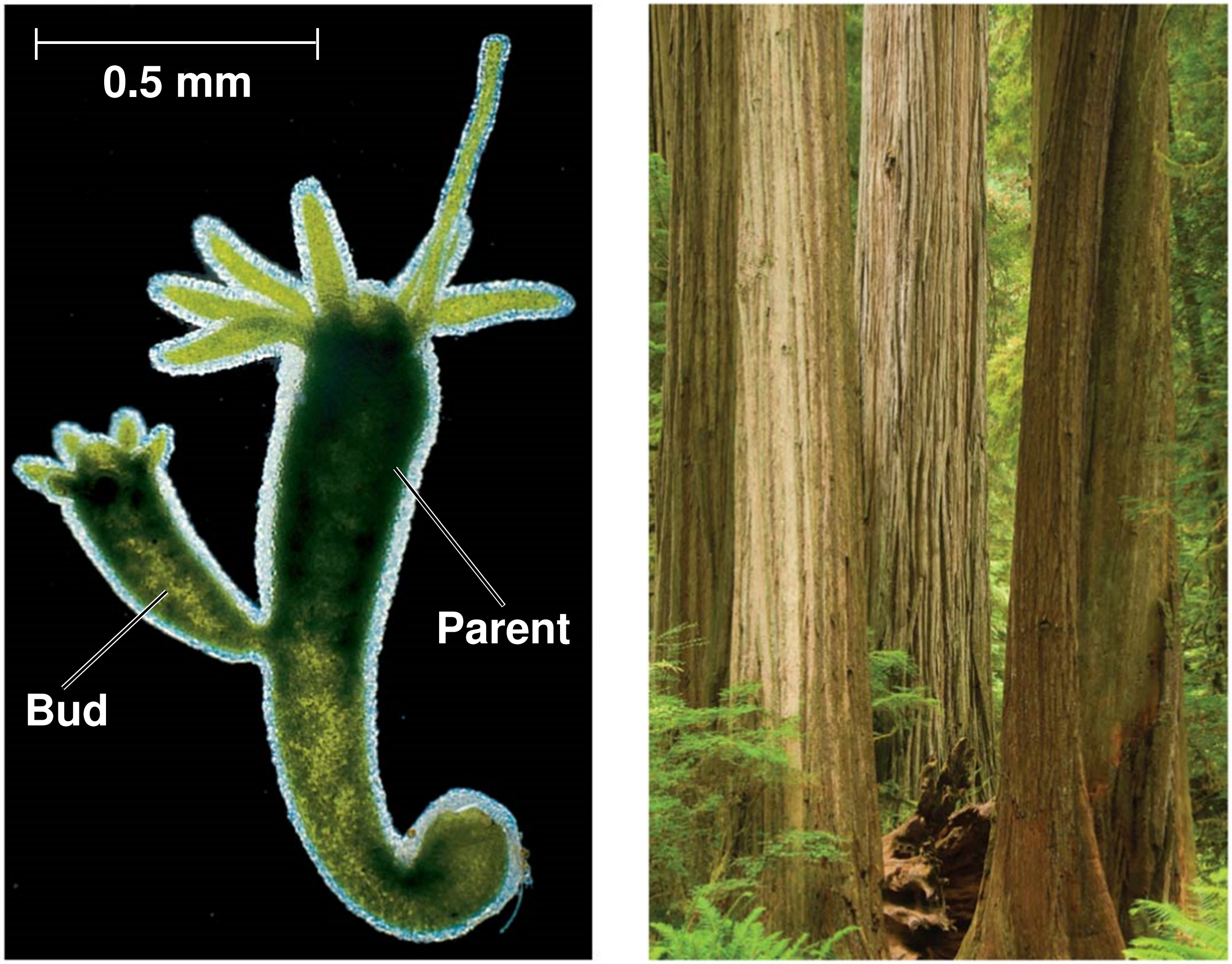
Comparison of Asexual and Sexual Reproduction

- In **asexual reproduction**, a single individual passes genes to its offspring without the fusion of gametes
  - Make exact genetic copies of themselves
- A **clone** is a group of genetically identical individuals from the same parent
- In **sexual reproduction**, two parents give rise to offspring that have unique combinations of genes inherited from the two parents
  - Genetic variation is an important consequence of sexual reproduction



Video: Hydra Budding

Figure 10.2



(a) Hydra

(b) Redwoods

Concept 10.2: Fertilization and meiosis alternate in sexual life cycles

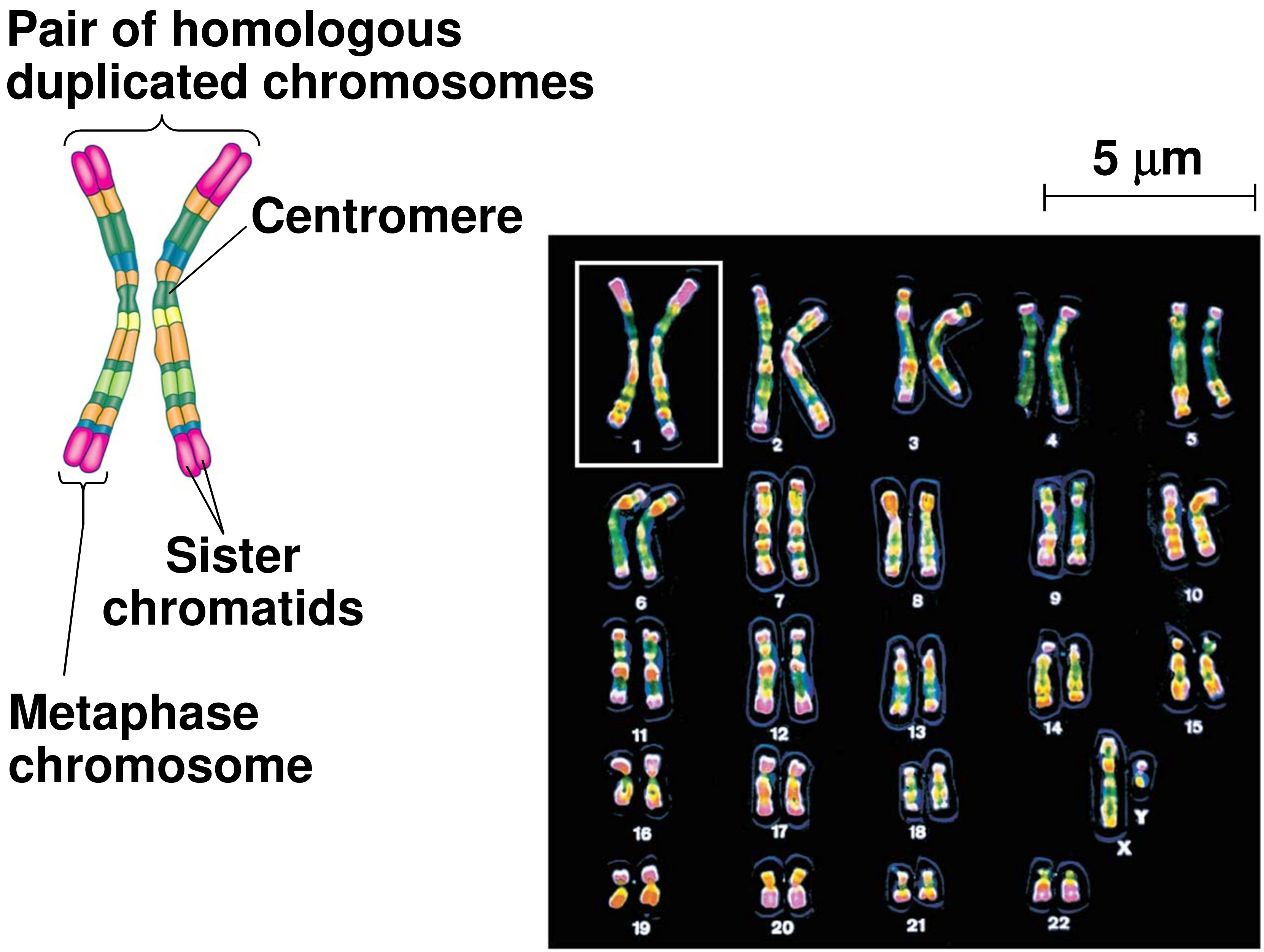
- A **life cycle** is the generation-to-generation sequence of stages in the reproductive history of an organism

Sets of Chromosomes in Human Cells

- Human somatic cells have 23 pairs of chromosomes
- A **karyotype** is an ordered display of the pairs of chromosomes from a cell
- The two chromosomes in each pair are called **homologous chromosomes**, or homologs
  - Chromosomes in a homologous pair are the same length and shape and carry genes controlling the same inherited characters

Figure 10.3b

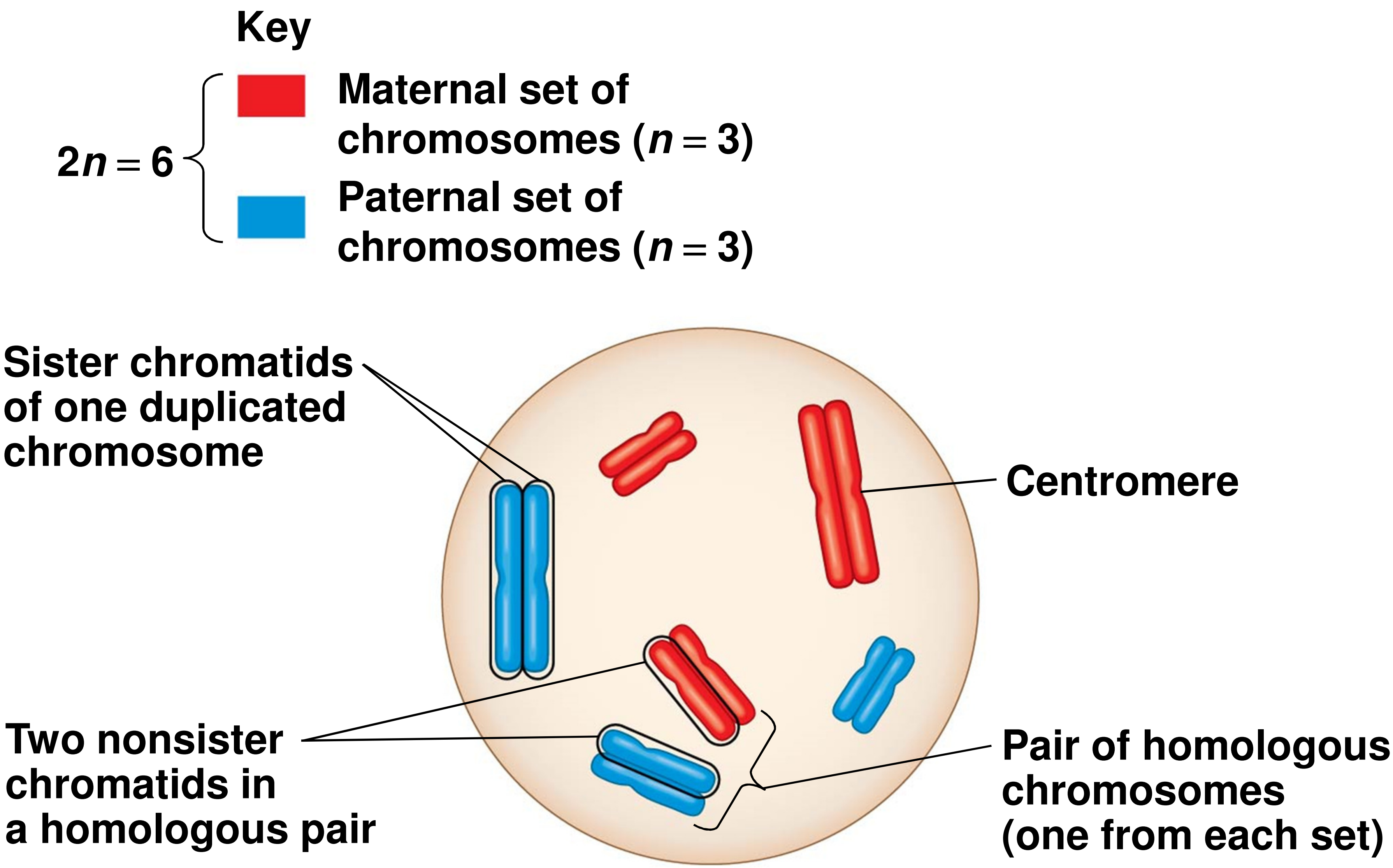
Technique



- The **sex chromosomes**, which determine the sex of the individual, are called X and Y
  - Human females have a homologous pair of X chromosomes (XX)
  - Human males have one X and one Y chromosome
- The remaining 22 pairs of chromosomes are called **autosomes**

- Each pair of homologous chromosomes includes one chromosome from each parent
  - The 46 chromosomes in a human somatic cell are two sets of 23
    - One from the mother and one from the father
- A **diploid cell** ($2n$) has two sets of chromosomes
  - For humans, the diploid number is 46 ($2n = 46$)
- In a cell in which DNA synthesis has occurred, each chromosome is replicated
  - Each replicated chromosome consists of two identical sister chromatids

Figure 10.4


Key
2n = 6
Maternal set of chromosomes (n = 3)
Paternal set of chromosomes (n = 3)
Sister chromatids of one duplicated chromosome
Centromere
Two nonsister chromatids in a homologous pair
Pair of homologous chromosomes (one from each set)

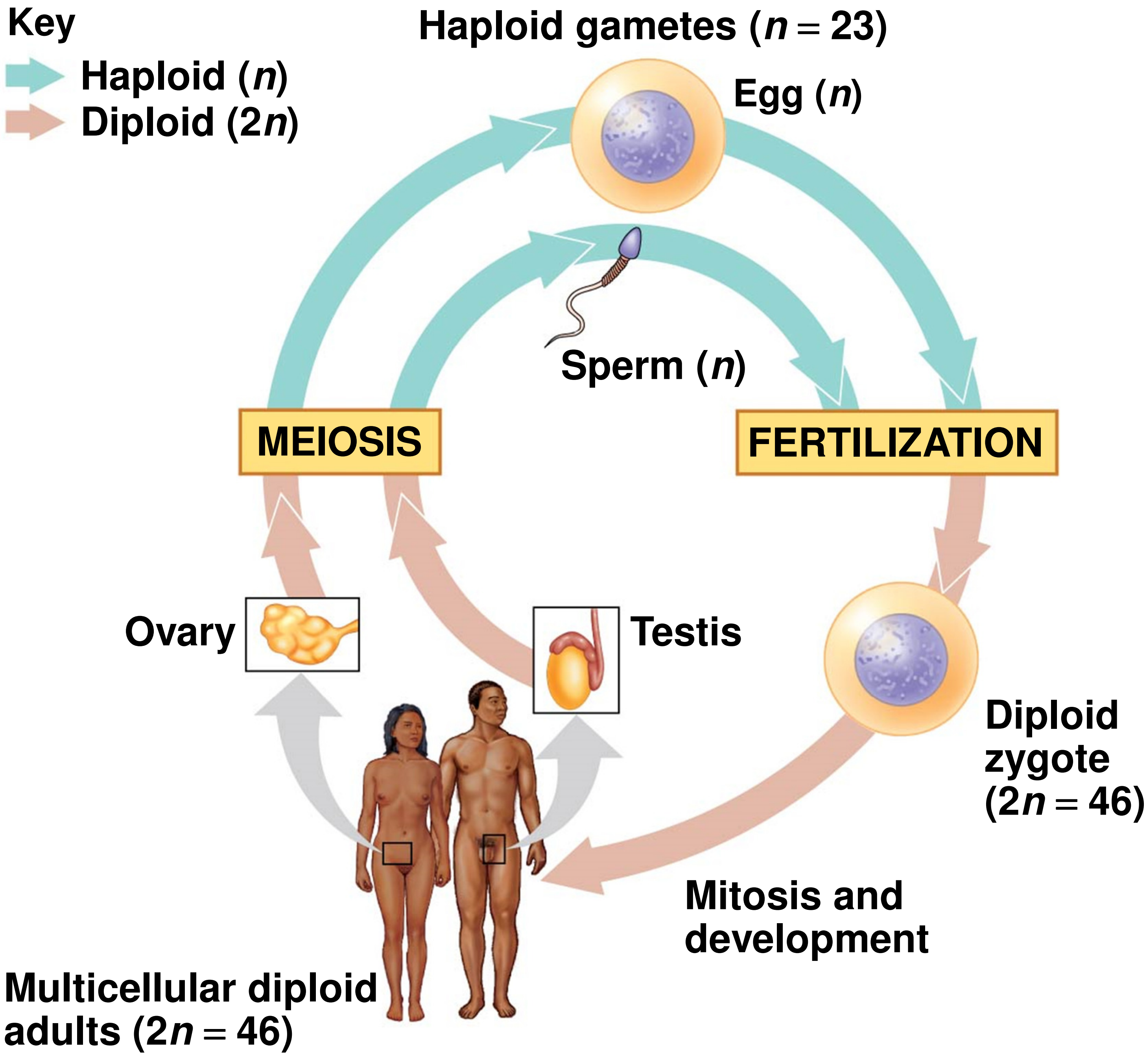
- A gamete (sperm or egg) contains a single set of chromosomes and is **haploid** (*n*)
  - For humans, the haploid number is 23 (n = 23)
- Each set of 23 consists of 22 autosomes and a single sex chromosome
  - In an unfertilized egg (ovum), the sex chromosome is X
  - In a sperm cell, the sex chromosome may be either X or Y

Behavior of Chromosome Sets in the Human Life Cycle

- **Fertilization** is the union of gametes (the sperm and the egg)
  - Starts the human life cycle
- The fertilized egg is called a **zygote**
  - Diploid
  - Has one set of chromosomes from each parent
- The zygote produces somatic cells by mitosis and develops into an adult

- At sexual maturity, the ovaries and testes produce haploid gametes
  - Gametes are the only types of human cells produced by **meiosis** rather than mitosis
- Meiosis reduces the number of sets of chromosomes, resulting in one set of chromosomes in each gamete
  - Otherwise, the number of chromosomes would double each time during fertilization
- Fertilization and meiosis alternate in sexual life cycles to maintain chromosome number

Figure 10.5

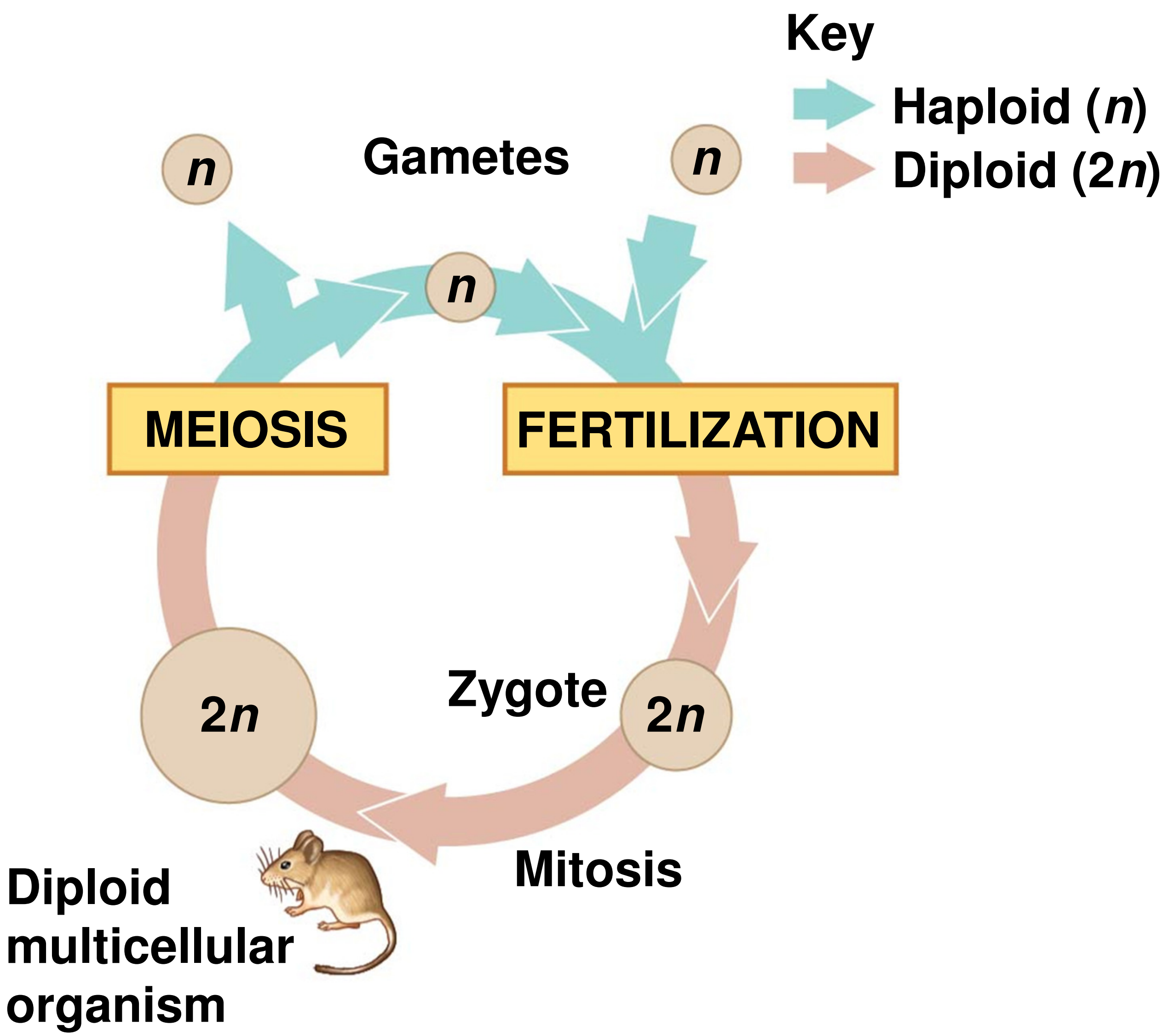

Key
Haploid (n)
Diploid (2n)
Haploid gametes (n = 23)
Egg (n)
Sperm (n)
MEIOSIS
FERTILIZATION
Ovary
Testis
Diploid
zygote
(2n = 46)
Mitosis and
development
Multicellular diploid
adults (2n = 46)

The Variety of Sexual Life Cycles

- The alternation of meiosis and fertilization is common to all organisms that reproduce sexually
- The three main types of sexual life cycles differ in the timing of meiosis and fertilization

1. In animals, gametes are the only haploid cells
   - They are produced by meiosis and undergo no further cell division before fertilization
   - Gametes fuse to form a diploid zygote that divides by mitosis to develop into a multicellular organism

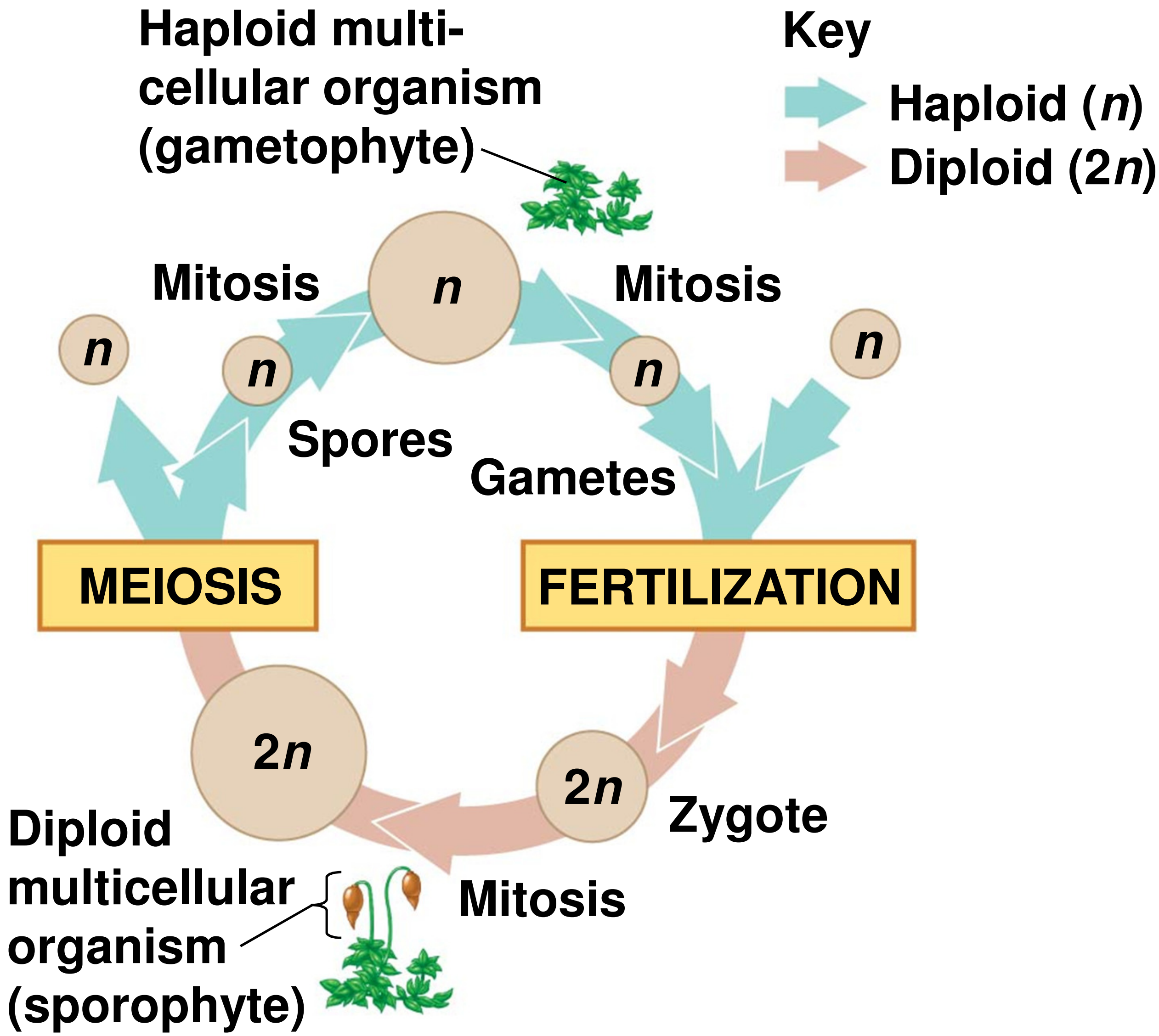
Figure 10.6a



(a) Animals

2. Plants and some algae exhibit an **alternation of generations**
   - This life cycle includes both a diploid and haploid multicellular stage
   - The diploid organism, called the *sporophyte*, makes haploid *spores* by meiosis
   - Each spore grows by mitosis into a haploid organism called a *gametophyte*
   - A gametophyte makes haploid gametes by mitosis
   - Fertilization of gametes results in a diploid sporophyte

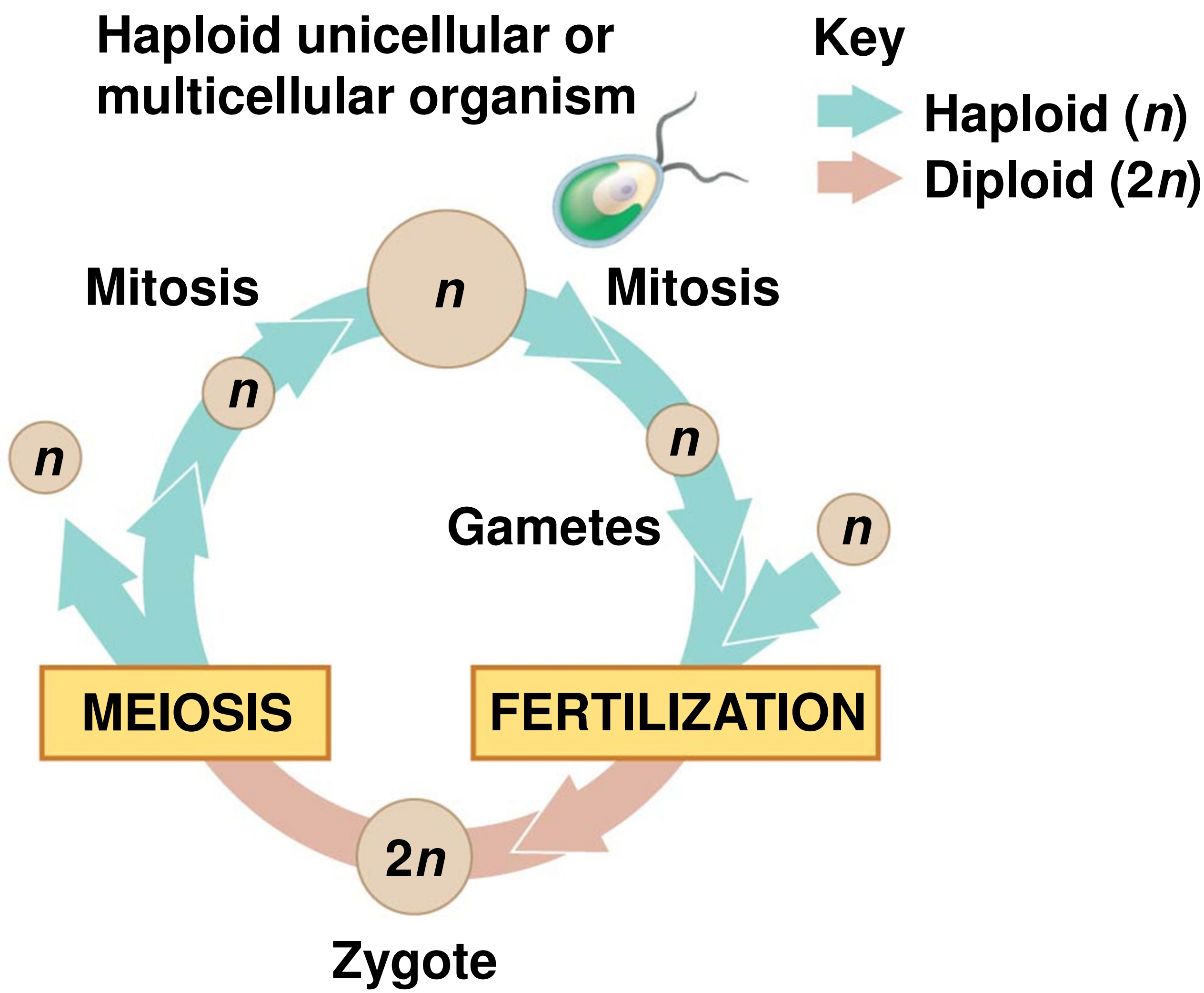
Figure 10.6b



(b) Plants and some algae

3. In most fungi and some protists, the only diploid stage is the single-celled zygote; there is no multicellular diploid stage
   - The zygote produces haploid cells by meiosis
   - Each haploid cell grows by mitosis into a haploid multicellular organism
   - The haploid adult produces gametes by mitosis

Figure 10.6c



(c) Most fungi and some protists

- Depending on the type of life cycle, either haploid or diploid cells can divide by mitosis
    - However, only diploid cells can undergo meiosis!
- In all three life cycles, the halving and doubling of chromosomes contribute to genetic variation in offspring

Concept 10.3: Meiosis reduces the number of chromosome sets from diploid to haploid

- Like mitosis, meiosis is preceded by the replication of chromosomes
- Meiosis takes place in two sets of cell divisions, called **meiosis I** and **meiosis II**
- The two cell divisions result in four daughter cells, rather than the two daughter cells in mitosis
- Each daughter cell has only half as many chromosomes as the parent cell

The Stages of Meiosis

- For a single pair of homologous chromosomes in a diploid cell, both members of the pair are duplicated
- The resulting sister chromatids are closely associated all along their lengths
- Remember,
  - Sister chromatids are IDENTICAL copies of the same chromosome
  - Homologs are individual chromosomes that were inherited from different parents
    - They have the same genes at the same loci, but are NOT identical copies
    - They may have different versions of those genes, each called an *allele*

Figure 10.7a

Interphase

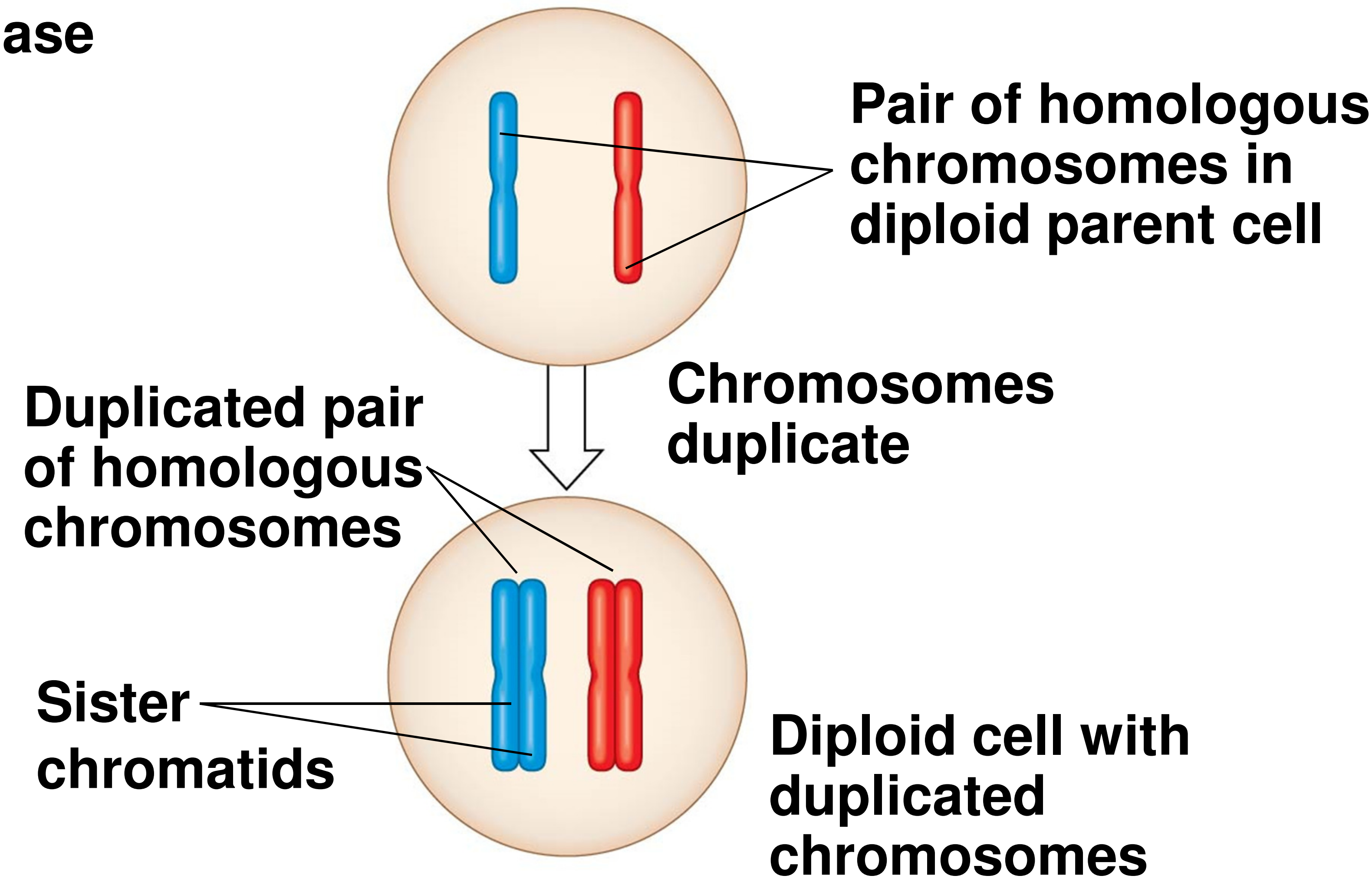
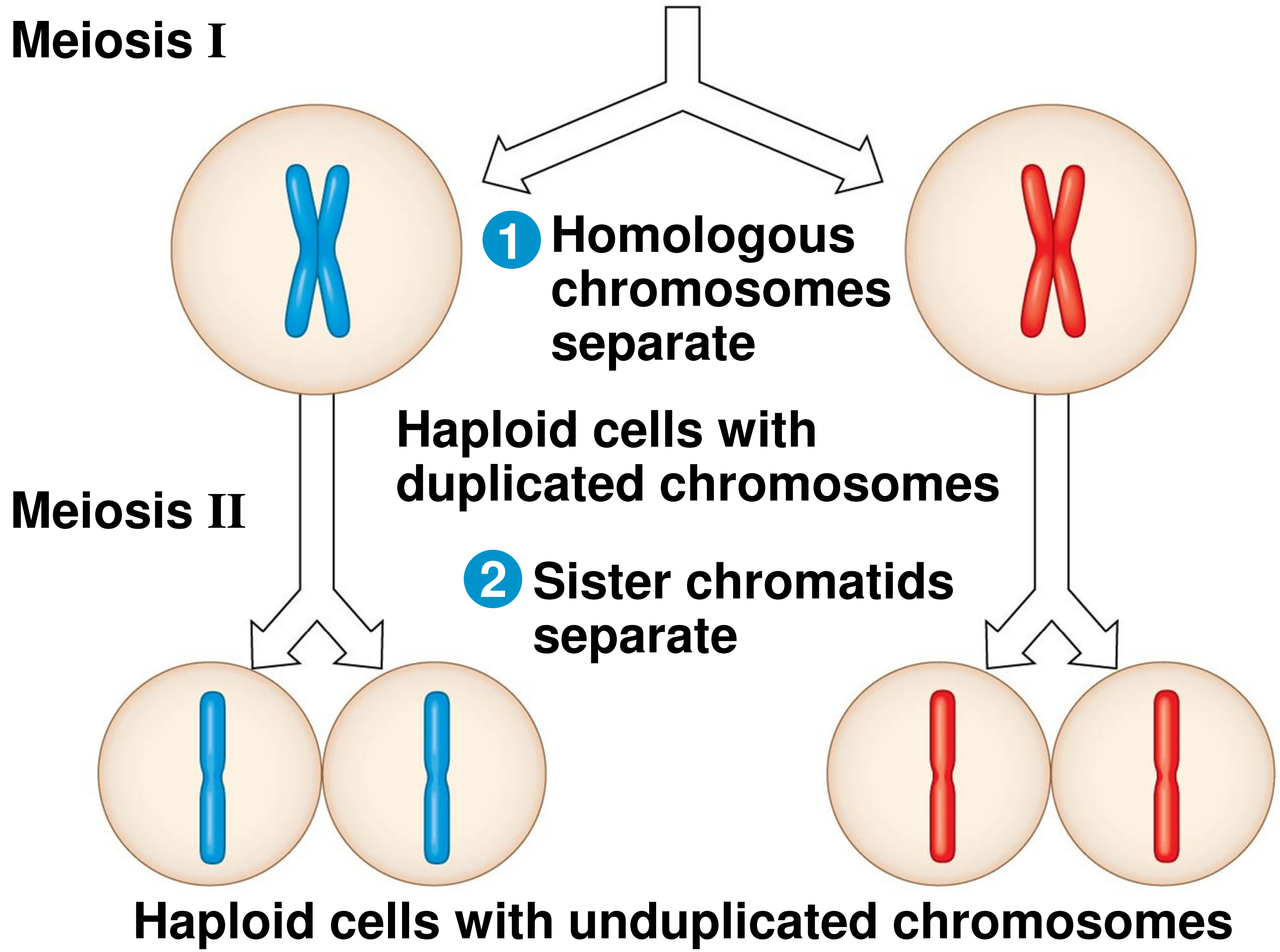
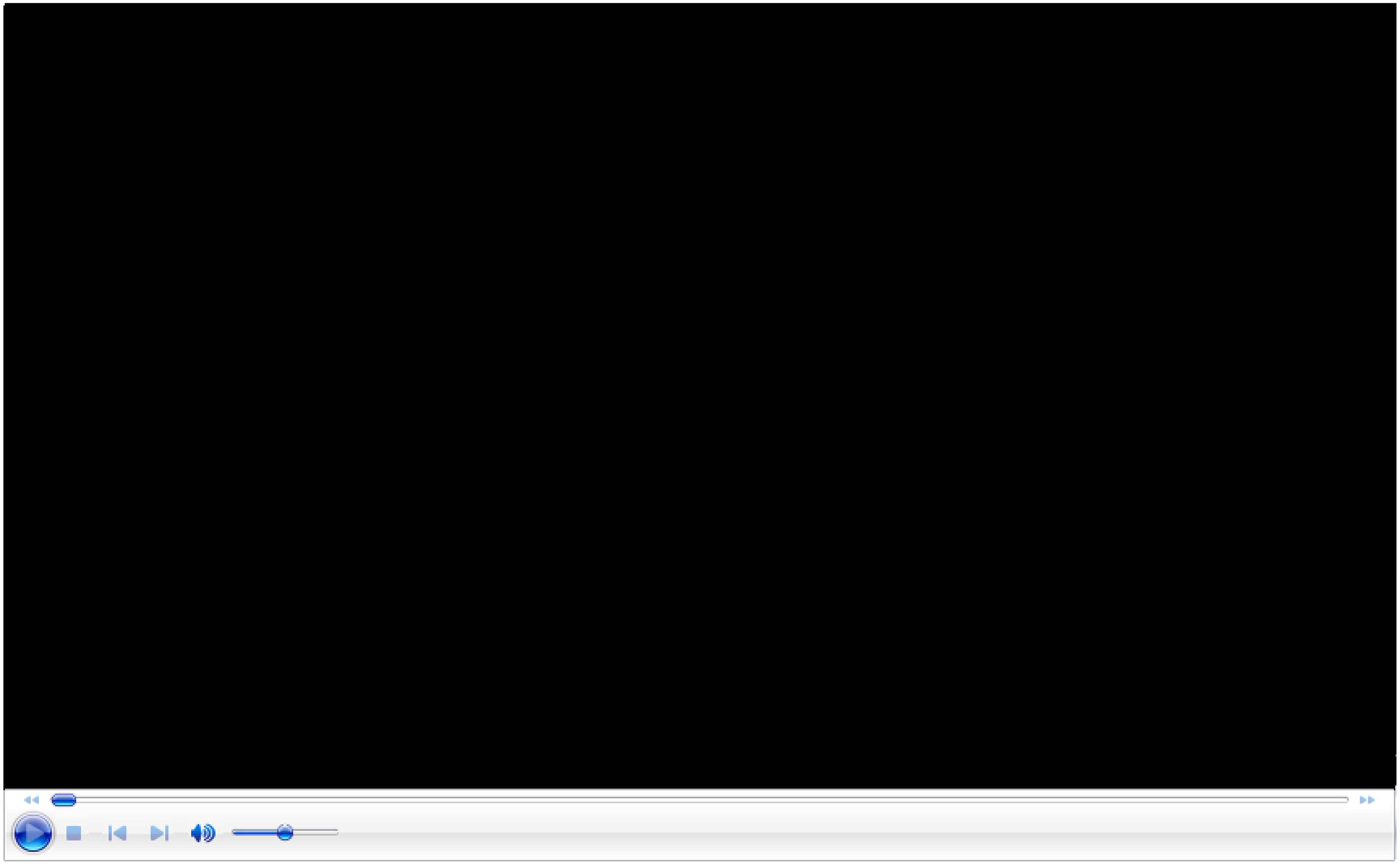


Figure 10.7b


Meiosis I
1 Homologous chromosomes separate
Haploid cells with duplicated chromosomes
Meiosis II
2 Sister chromatids separate
Haploid cells with unduplicated chromosomes

- Meiosis halves the total number of chromosomes very specifically
  - It reduces the number of sets from two to one, with each daughter cell receiving one set of chromosomes
- In the first meiotic division, homologous pairs of chromosomes pair and separate
- In the second meiotic division, sister chromatids of each chromosome separate
- Four new haploid cells are produced as a result



Video: Meiosis

Figure 10.8a

MEIOSIS I: Separates homologous chromosomes

Prophase I	Metaphase I	Anaphase I	Telophase I and Cytokinesis

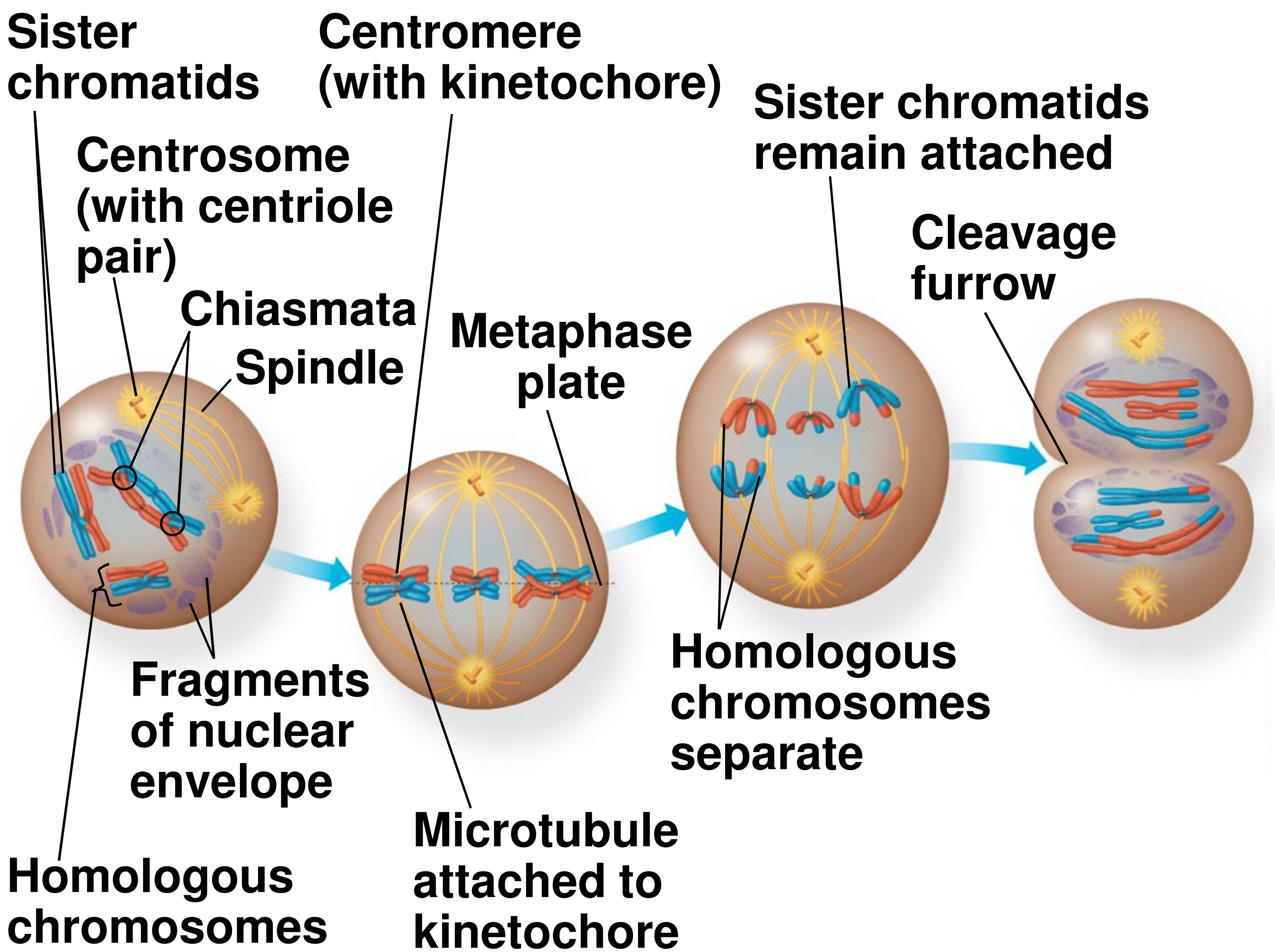
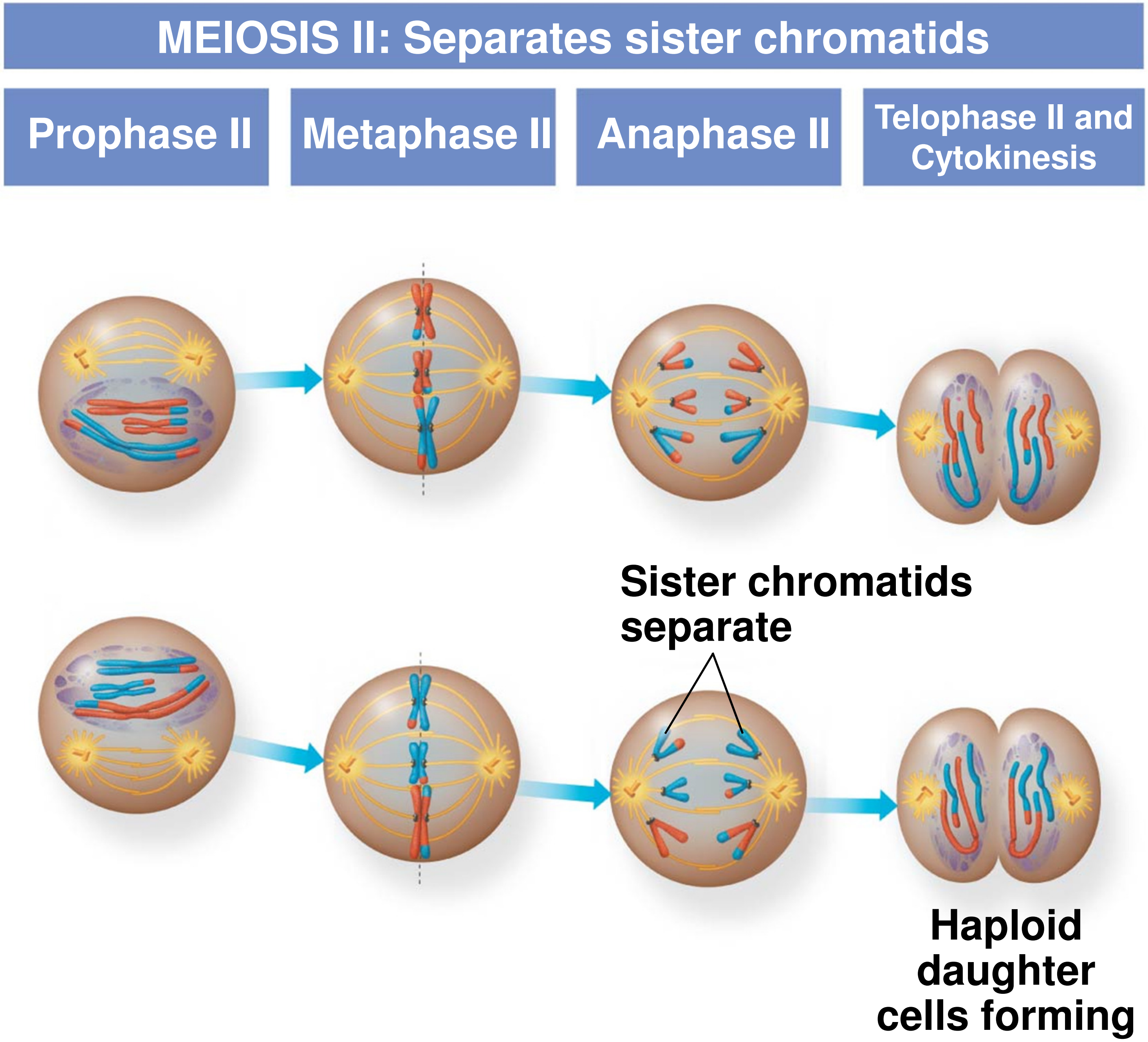


Figure 10.8b


MEIOSIS II: Separates sister chromatids
Prophase II
Metaphase II
Anaphase II
Telophase II and Cytokinesis
Sister chromatids separate
Haploid daughter cells forming

Prophase I

- Chromosomes begin to condense
- In **synapsis**, homologous chromosomes loosely pair up, aligned gene by gene
- In **crossing over**, nonsister chromatids exchange DNA segments
- Each homologous pair has one or more X-shaped regions called **chiasmata**
  - Chiasmata exist at points where crossing over has occurred

Metaphase I

- In metaphase I, tetrads line up at the metaphase plate, with one chromosome facing each pole
- Microtubules from one pole are attached to the kinetochore of one chromosome of each tetrad
- Microtubules from the other pole are attached to the kinetochore of the other chromosome

Anaphase I

- In anaphase I, pairs of homologous chromosomes separate
- One chromosome moves toward each pole, guided by the spindle apparatus
- Sister chromatids remain attached at the centromere and move as one unit toward the pole

Telophase I and Cytokinesis

- In the beginning of telophase I, each half of the cell has a haploid set of chromosomes
  - Each chromosome still consists of two sister chromatids
- Cytokinesis usually occurs simultaneously, forming two haploid daughter cells

- In animal cells, a cleavage furrow forms
- In plant cells, a cell plate forms
- No chromosome replication occurs between the end of meiosis I and the beginning of meiosis II
  - Because the chromosomes are already replicated!

- Division in meiosis II also occurs in four phases
  - Prophase II
  - Metaphase II
  - Anaphase II
  - Telophase II and cytokinesis
- Meiosis II is very similar to mitosis

Prophase II

- In prophase II, a spindle apparatus forms
- In late prophase II, chromosomes (each still composed of two chromatids) move toward the metaphase plate

Metaphase II

- In metaphase II, the sister chromatids are arranged at the metaphase plate
- Because of crossing over in meiosis I, the two sister chromatids of each chromosome are no longer genetically identical
- The kinetochores of sister chromatids attach to microtubules extending from opposite poles

Anaphase II

- In anaphase II, the sister chromatids separate
- The sister chromatids of each chromosome now move as two newly individual chromosomes toward opposite poles

Telophase II and Cytokinesis

- In telophase II, the chromosomes arrive at opposite poles
- Nuclei form, and the chromosomes begin decondensing

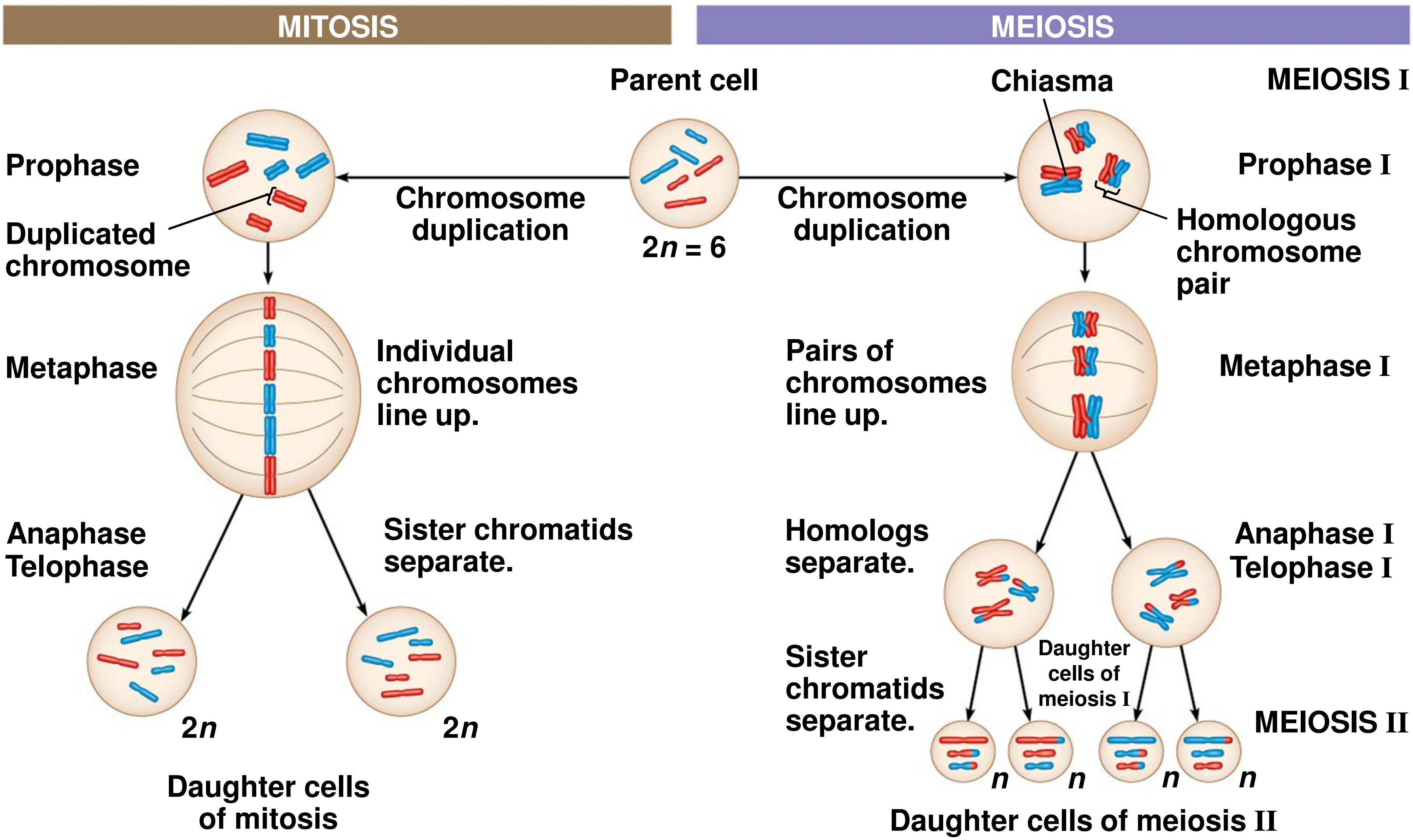
- At the end of meiosis, there are
  - Four daughter cells
  - Each with a haploid set of unduplicated chromosomes
- Each daughter cell is genetically distinct from the others and from the parent cell

A Comparison of Mitosis and Meiosis

- Mitosis conserves the number of chromosome sets, producing cells that are genetically identical to the parent cell
- Meiosis reduces the number of chromosome sets from two (diploid) to one (haploid), producing cells that differ genetically from each other and from the parent cell
- Meiosis includes two divisions after replication, each with specific stages

- Three events are unique to meiosis, and all three occur in meiosis I
  - **Synapsis and crossing over** in prophase I: Homologous chromosomes physically connect and exchange genetic information
  - **Homologous pairs at the metaphase plate**: Homologous pairs of chromosomes are positioned there in metaphase I
  - **Separation of homologs** during anaphase I

Figure 10.9a



MITOSIS
MEIOSIS
Parent cell
Chiasma
MEIOSIS I
Prophase
Duplicated chromosome
Chromosome duplication
2n = 6
Chromosome duplication
Prophase I
Homologous chromosome pair
Metaphase
Individual chromosomes line up.
Pairs of chromosomes line up.
Metaphase I
Anaphase Telophase
Sister chromatids separate.
Homologs separate.
Anaphase I Telophase I
Sister chromatids separate.
Daughter cells of meiosis I
MEIOSIS II
2n
2n
n
n
n
n
Daughter cells of mitosis
Daughter cells of meiosis II

Figure 10.9b

SUMMARY		
Property	**Mitosis**	**Meiosis**
DNA replication	Occurs during interphase before mitosis begins	Occurs during interphase before meiosis I begins
Number of divisions	One, including prophase, prometaphase, metaphase, anaphase, and telophase	Two, each including prophase, metaphase, anaphase, and telophase
Synapsis of homologous chromosomes	Does not occur	Occurs during prophase I along with crossing over between nonsister chromatids; resulting chiasmata hold pairs together due to sister chromatid cohesion
Number of daughter cells and genetic composition	Two, each diploid (2*n*) and genetically identical to the parent cell	Four, each haploid (*n*), containing half as many chromosomes as the parent cell; genetically different from the parent cell and from each other
Role in the animal body	Enables multicellular adult to arise from zygote; produces cells for growth, repair, and, in some species, asexual reproduction	Produces gametes; reduces number of chromosome sets by half and introduces genetic variability among the gametes

- Meiosis I is called the reductional division because it halves the number of chromosome sets per cell from diploid (2*n*) to haploid (*n*)
- Meiosis II is called the equational division because the haploid cells divide to produce haploid daughter cells
- The mechanism of sister chromatid separation in meiosis II is identical to that in mitosis

Concept 10.4: Genetic variation produced in sexual life cycles contributes to evolution

- Mutations (changes in an organism’s DNA) are the original source of genetic diversity
- Mutations create different versions of genes called alleles
- Reshuffling of alleles during sexual reproduction produces genetic variation

Origins of Genetic Variation Among Offspring

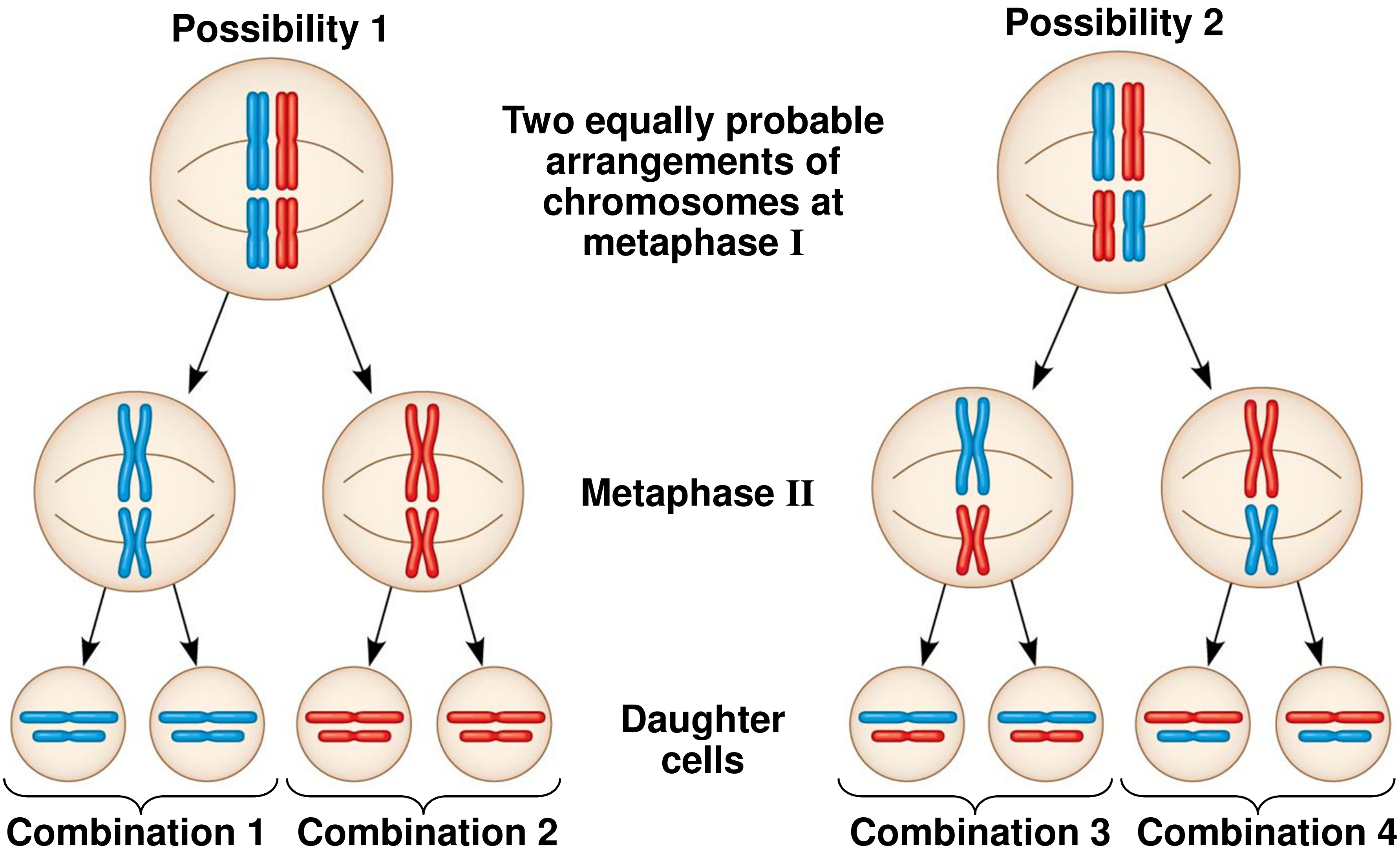
- The behavior of chromosomes during meiosis and fertilization is responsible for most of the variation that arises in each generation
- Three mechanisms contribute to genetic variation

1. Independent assortment of chromosomes
2. Crossing over
3. Random fertilization

1. Independent Assortment of Chromosomes

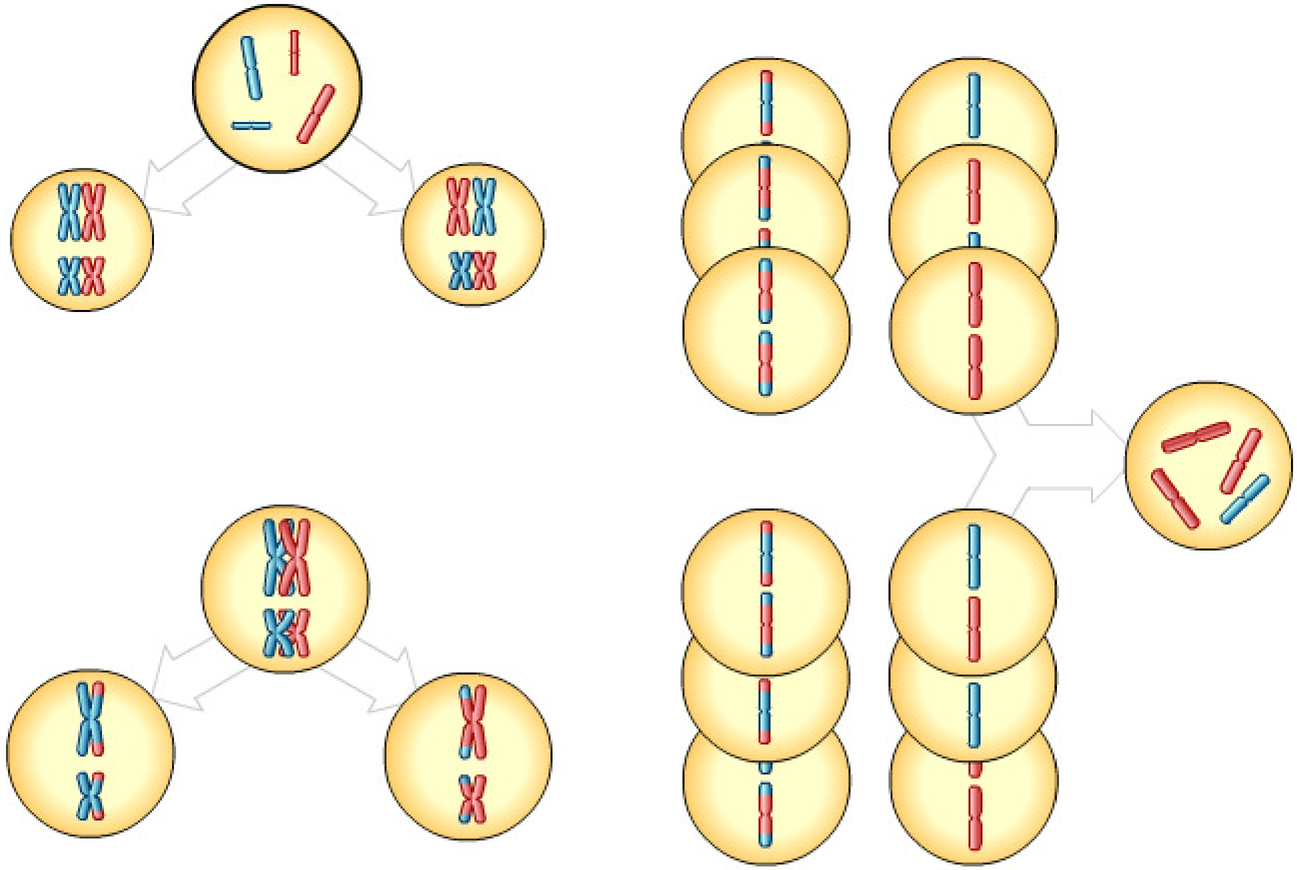
- Homologous pairs of chromosomes orient randomly at metaphase I of meiosis
- In *independent assortment*, each pair of chromosomes sorts maternal and paternal homologs into daughter cells independently of the other pairs
- The number of combinations possible when chromosomes assort independently into gametes is 2^n, where *n* is the haploid number
  - For humans (*n* = 23), there are more than 8 million (2^{23}) possible combinations of chromosomes

Figure 10.10-3



2. Crossing Over

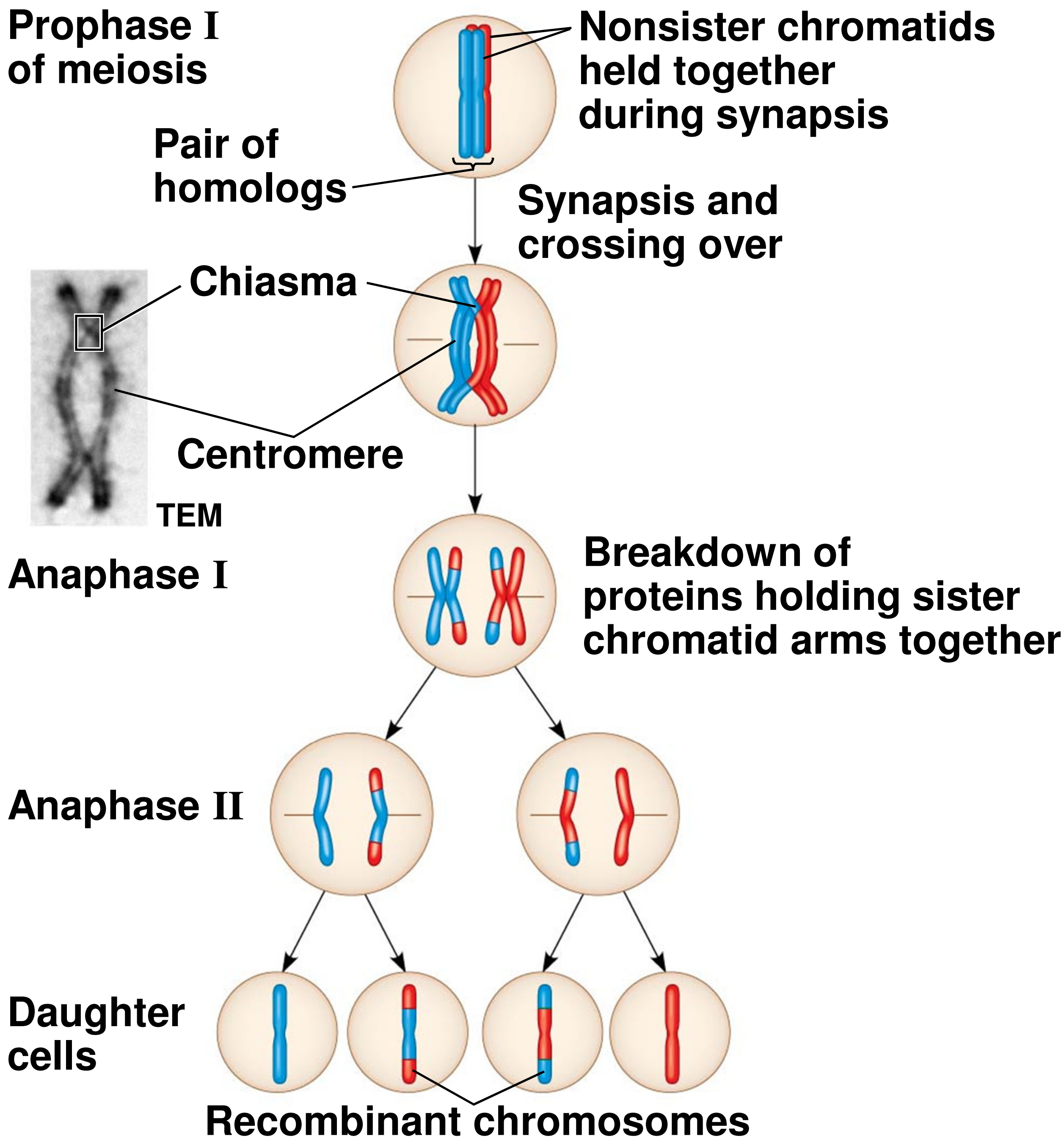
- Crossing over produces **recombinant chromosomes**, which combine DNA inherited from each parent
- Crossing over begins very early in prophase I, as homologous chromosomes pair up gene by gene
- In crossing over, homologous portions of two nonsister chromatids trade places
- Crossing over contributes to genetic variation by combining DNA, producing chromosomes with new combinations of maternal and paternal alleles



Animation: Genetic Variation

Right click slide / Select play

Figure 10.11-5



3. Random Fertilization

- Random fertilization adds to genetic variation because any sperm can fuse with any ovum (unfertilized egg)
- The fusion of two gametes (each with 2^{23} possible chromosome combinations from independent assortment) produces a zygote with any of about 70 trillion diploid combinations
  - Crossing over adds even more variation
- Each zygote has a unique genetic identity

The Evolutionary Significance of Genetic Variation Within Populations

- Natural selection results in the accumulation of genetic variations favored by the environment
  - Individuals best suited to the environment leave the most offspring, thereby transmitting their genes
- Sexual reproduction contributes to the genetic variation in a population, which originates from mutations

- Asexual reproduction is less expensive than sexual reproduction
- Nonetheless, sexual reproduction is nearly universal among animals
- Overall, genetic variation is evolutionarily advantageous